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Dry frictional contact of metal asperities: A dislocation dynamics analysis

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ABSTRACT

Discrete dislocation plasticity simulations are performed to investigate the static frictional behavior of a metal asperity on a large single crystal, in contact with a rigid platen. The focus of this study is on understanding the relative importance of contact slip opposed to plasticity in a single asperity at the micrometer size scale, where plasticity is size dependent.

Slip of a contact point is taken to occur when the shear traction exceeds the normal traction at that point times a microscopic friction coefficient. Plasticity initiates through the nucleation of dislocations from Frank-Read sources in the metal and is modeled as the collective motion of edge dislocations.

Results show that plasticity can delay or even suppress full slip of the contact. This generally happens when the friction coefficient is large. However, if the flattening depth is sufficiently large to induce nucleation of a large dislocation density, slip is suppressed even when the friction coefficient is very small. This study also shows that when self-similar asperities of different size are flattened to the same depth and subsequently loaded tangentially, their frictional behavior appears size independent. However, when they are submitted to the same contact pressure, smaller asperities slip while larger asperities deform plastically.

1. Introduction

Friction between two rough surfaces resists their relative motion. The surfaces respond to an applied sliding force by deforming elastically and plastically and by eventually loosing adhesion. Plastic deformation and loss of adhesion are competing mechanisms: if the contact roughness can respond to the applied load through plastic deformation, slip at the interface might not take place, albeit at the macroscale the bodies appear displaced relative to each other. The occurrence of slip will clearly depend also on the interfacial energy between the contacting surfaces, and therefore on the materials in contact.

The classical Amontons–Coulomb law of friction states that the onset of sliding of a macro-scale contact occurs when the ratio between the tangential force f and the applied normal force f_n exceeds the static friction coefficient μ. This statement relies on the assumption that the friction coefficient μ is a constant and therefore a property of the interface, and that it is not important how the friction force and the normal force vary along the contact, since only forces averaged along the contact are considered. Along the same line, Bowden and Tabor [1] stated that the friction force is proportional to the true contact area C, where the proportionality constant is the friction strength. Again, variations in the shear stress along the contact are not assumed to be significant or relevant in the friction process.

However, when two surfaces are under contact loading, it has been shown by molecular dynamics [2] and discrete dislocation plasticity simulations [3] that the contact shear stress varies significantly along the apparent contact area. This is mainly attributed to the fact that the true contact area is highly patchy at the micrometer scale. Unfortunately, the measurement of true contact area is far from easy, especially when both materials in contact are non transparent. While the average size of the contact area can be obtained by acoustic or electroconductivity measurements, details of the contact area can only be captured by means of microscopy if the contacting materials are transparent, made for instance of acrylate [4]. A technique that is often used in biomechanics to measure areas and pressures under moderate applied forces involves the use of pressure-sensitive Fuji film [5]. More

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sophisticated experimental techniques are those devised by the groups of Fineberg [6] and of Bonn [7]. The first groups make use of a laser beam to detect the true contact area between PMMA blocks, the second relies on the enhancement of the fluorescence of rigidochromic probe molecules attached to one of the contacting surfaces. The experimental contact surfaces measured with the various techniques have always a patchy nature, irrespectively of the material tested. Consequently, it is to be expected that for metals the contact pressure profile is indeed a collection of high peaks, instead of a smooth pressure distribution as is predicted by continuum plasticity simulations, e.g. Ref. [8].

The aim of this paper is to investigate the frictional behavior of a single microscale asperity protruding from the surface of a metal body, accounting for plasticity. Plastic deformation has been observed experimentally when flattening spherical single [9] and multi-asperities [10] with moderate contact loads. The numerical technique used in this study is the discrete dislocation plasticity method [11] which can capture key features of microscale plasticity: size effects [12–14], strain gradient effects [15–17] as well as local stress peaks in the surface pressure [12,18]. Attention here will mainly focus on the competition between plasticity and slip, for micron-scale asperities of different size.

This work is an extension of previous discrete dislocation plasticity studies where a single or multiple asperities were plastically sheared, under sticking contact conditions [19,20]. Due to the full sticking nature of the contact, a very high shear stress was reached locally on the contact. Here, we use a contact condition that, instead, allows for local sliding. Inspired by the Cattaneo–Mindlin problem [21,22], the contact will slip when the contact shear stress exceeds the normal shear stress multiplied by a constant friction coefficient. The difference with the Cattaneo–Mindlin problem and with the classical Amonton's law is that instead of using average stresses on the contact, local stresses will be computed at each point in contact. For simplicity in the interpretation of the results, the asperities are firstly flattened with a rigid platen, such as to reach elastic or plastic deformation, and subsequently loaded tangentially by rigidly displacing the platen. Also, the asperity is taken to be flat initially, so that the contact area stays constant during the simulation. This choice is motivated by the fact that flattening asperities with sinusoidal profile leads to a highly fragmented contact area, with a large central contact region surrounded by many small contact patches. The contact patches are a consequence of dislocations leaving behind crystallographic steps at the surface [18]. Using such a fragmented contact area as the starting point for the shearing simulations has the drawback that the size of the small contact patches can be an order of magnitude smaller than the large contact area, and therefore the question arises on whether the various contact patches should have the same friction coefficient, and if not, how much should they differ. Additionally, the size and location of the contact patches is stochastic and obtain statistically significant results would require a large number of simulations.

A similar modeling approach for dry static friction was used by Deshpande et al. [23] who investigated the behavior of flat and sinusoidal microscale contacts on a flat metal single crystal. The contact was mimicked by means of a cohesive zone. De-adhesion of the interface was modeled via a shear traction versus tangential displacement relationship, which is characterized by a cohesive strength, independent of the normal load acting on the contact. The paper [23] has the merit of showing that the friction stress is dominated by slip at small contact size (smaller than ≈ 40 nm), and by plasticity at large contact size (larger than $\approx 4\mu$ m). However, the assumption that the cohesive strength τ is independent of both contact size and normal loading, leads to very high friction coefficients ($\mu{=}\tau/P_m$ reaches values much above 10 in Ref. [23]). It should be noted that this is not in conflict with the Bowden–Tabor interpretation of the friction force being the product of friction strength and contact area, because they assumed that the contact area increases with increasing normal loading. Nevertheless, in order to avoid any possible confusion on this, we here introduce a friction coefficient that relates the shear traction to the local contact pressure.

2. Formulation

2.1. Boundary value problem

A rigid platen is in contact with a large metal single crystal through a single rectangular asperity that protrudes from the surface of the metal crystal (see Fig. 1). The length of the crystal is $L = 1000\,\mu$m and its height $h = 50\,\mu$m. The loading consists of two steps: first the asperity is flattened by prescribing vertical displacement of the rigid platen, then the platen is displaced tangentially. During flattening,

$$u_2(x_1, h + h_p) = -\int_C v_2 \mathrm{d}t, \tag{1}$$

where v_2 is the velocity of the rigid platen in the vertical direction and $C{:=}[-w/2, w/2]$ is the contact area. Outside the contact region, the top surface is traction free. The boundary conditions at the bottom are:

$$u_1 = u_2 = 0, \quad \text{on} \quad x_2 = 0. \tag{2}$$

The traction distribution along the contact normal to the platen determines the flattening force F_n (per unit of out-of-plane depth):

$$F_n := -\int_C \sigma_{22} \mathrm{d}x_1. \tag{3}$$

Similarly, the shear force is calculated as

$$F_s := \int_C \sigma_{12} \mathrm{d}x_1. \tag{4}$$

After flattening, a tangential displacement is imposed at the contact by prescribing

$$u_1(x_1, h + h_p) = \int_C v_1 \mathrm{d}t, \tag{5}$$

$$u_2(x_1, h + h_p) = u_0, \quad x_1 \in C, \tag{6}$$

where v_1 is the velocity of the platen in the horizontal direction and

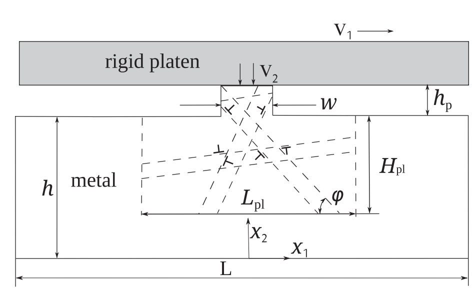

Fig. 1. Two-dimensional model of a rectangular asperity protruding from a large crystal flattened and sheared by a rigid platen.